AN2804
Application note

Virtual current control loop for L9374-L9375 coil driver kit in ABS-ESC control unit

Introduction

In the conventional hydraulic modulator for ABS-ESC control units, the 6 inlet valves (also known as ISO and/or TC-ISO valves), that is, the 4 devoted to the ABS/TCS functions and the other 2 valves devoted to the ESC functions, need a strict control of the coil energizing current. From the point of view of the electronic components involved in the ABS-ESC system partitioning, the above specification means to have a coil driver kit with 6 current regulated channels. The current regulation specification guarantees to have in the coil, driving the opening/closing of the on-off solenoid valve, the same energizing current against supply voltage changes, temperature gradient, "stiction" phenomena inside the valve due, for instance, to the aging and/or waste of the hydraulic and mechanical components (e.g. brake fluid, ball, armature, spring,…) involved into the valve working.

In this work, we propose a coil driver kit, composed by L9374-L9375, for new generation ABS/ESC control unit. The L9374 is a smart quad low side driver with 2 current regulated channels (accuracy is about 6%) and 2 PWM channels. On the other hand, the L9375 is an octal low side driver having 4 PWM channels and 4 conventional on-off switch channels. In order to allow the L9374-L9375 kit to work as there are 6 current regulated channels, we conceived a SW library, implemented by ST10252M microcontroller, that exploits data (these data are available on the MISO bus of the SPI) coming from the 2 current regulated channels of L9374 to calibrate the 4 PWM channels of L9375 so that they can work as having a current regulation loop. This virtual current control loop has been tested in different working conditions of the coil drivers:

- considering different supply voltages during the calibration and during the actuation of the virtual current regulated channels of L9375;
- simulating different temperature gradients;
- simulating temperature mismatches between the coil driven by a current regulated channel of L9374 and the coil driven by a virtual current regulated channel of L9375;
- considering several calibration timing and current set-points;
- taking into account different hydraulic modulators (Bosch, TRW).

Basically, the results show a satisfactory behavior of the virtual current control loop. In all the test conditions taken into account, it comes out an accuracy of the virtual current control loop that is similar to the nominal accuracy of the 2 current regulated channels of the L9374.

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1 L9374 and L9375 summary description

The L9374 is a smart quad low side driver with integrated free-wheeling diodes (see block diagram in figure 1). The switching of the channels is programmable via SPI (Serial Peripheral Interface). The main time base is given by an external clock via CLKin. The Clock Unit monitors this external clock and provides the system clock for all timings. A Synchronization Unit is used to monitor the SPI communication and provides a sync signal for the channel activation. The Output Duty Cycle for each channel can be programmed individually and will be activated by the Set Point Unit. Is possible to program two output Duty Cycles per channel with a block of 16 SPI commands as well as an individual Duration Time for each channel actuation. The PWM Controller translates the programmed digital duty cycle value in a PWM signal which controls the output. For the current regulated channels the target current value is programmed. It is also possible to program two different target currents. The target current is compared with the real load current. The output duty cycle is then calculated with an ALU. As base for the calculation a load model is used to take into account the variation of the real load versus the load assumption done into the first SPI transfers setting properly the command register of address 15 (see configuration register 3). Moreover, the L9374 ALU exploits respectively:

- measurement of the supply voltage (see VD status register of address 5);
- measurement of the voltage drop on the free-wheeling diode (see V_FWD status register of address 10);
- measurement of the sense resistor (see Rs status register of address 11) used to monitor the current on the Q3 and Q4 channels for the current control loop of the L9374.

All channels are equipped with a load Diagnostic. This allows to detect an open load in off condition as well as an under current in on condition. The power stage is protected against over current and over temperature. A weak connection in power ground or in the recirculation path is monitored. All monitored functions can be read out in a serial diagnostic protocol dedicated for each channel via SPI.

The L9375 is an octal low side driver with integrated recirculation diodes for PWM controlled channels, that is, Q5, Q6, Q7 and Q8. On the other hand, the channels Q1, Q2, Q3 and Q4 are configured as switching channels (see figure 2). To achieve a fast switch off a high voltage output clamp is implemented for a rapid free-wheeling if the inductive load. The switch on time can be programmed via SPI. The L9375 have the same features of the L9374 except for the current control of the channels of L9374.

Figure 1. L9374 application block diagram

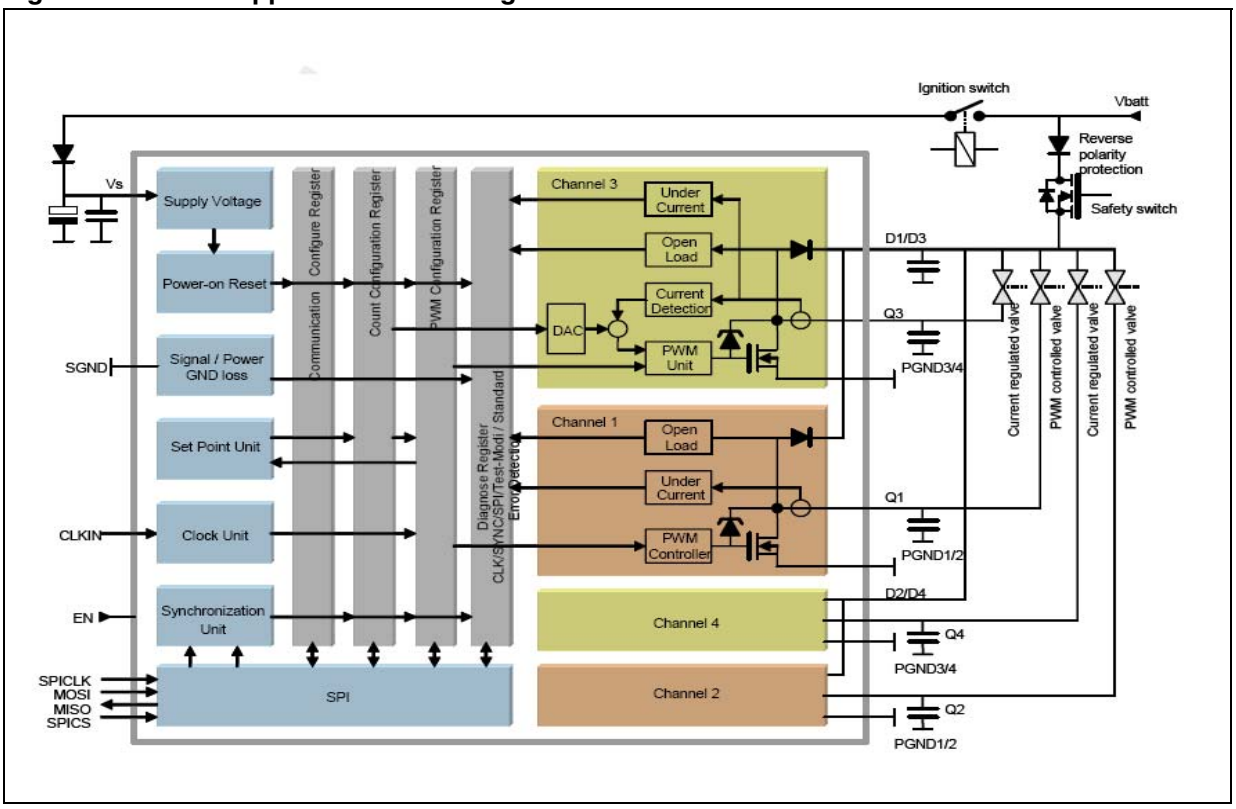
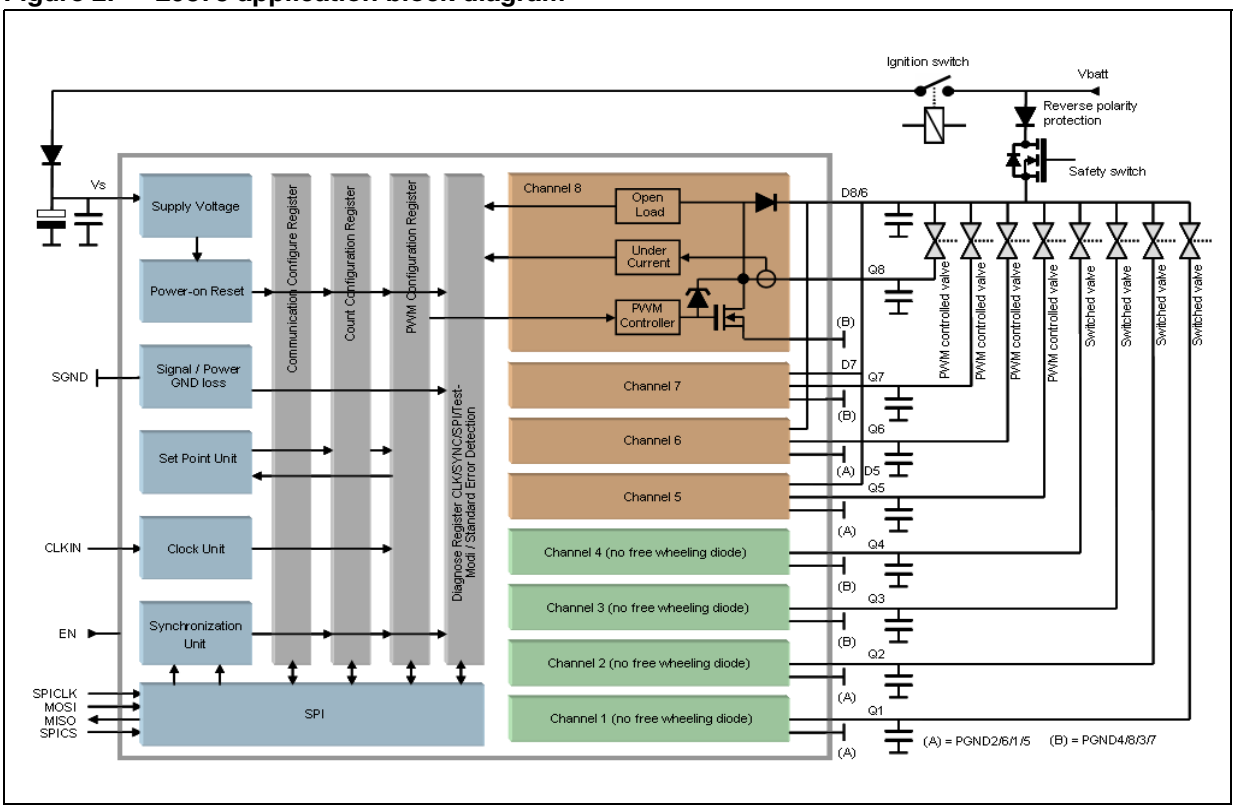


Figure 2. L9375 application block diagram



2 VCCL: plan of accuracy evaluation

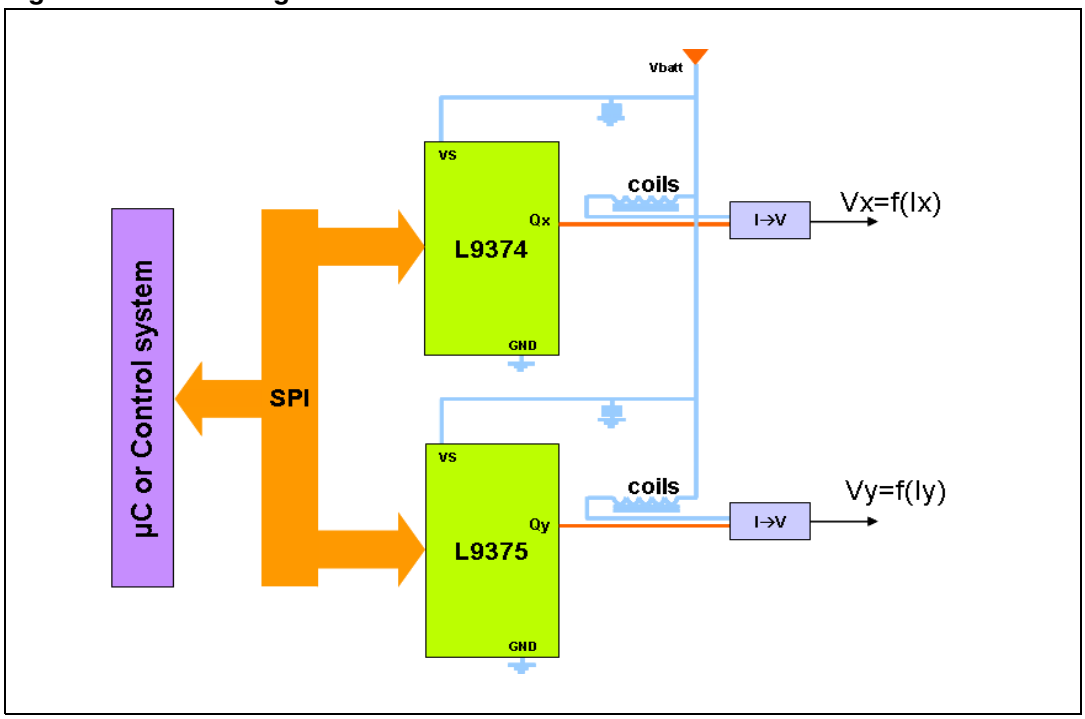
The idea behind the VCCL is to use the information coming from the current feedback of the Q3 and Q4 channels of L9374 in order to wrap the PWM channels of L9375 with a pseudo current control loop implemented by the microcontroller of the ABS/ESC control unit. In the *Figure 3*, the block diagram of the VCCL is described:

- set-up with a system microcontroller that works as the Master of the SPI communication with the Slaves, L9374 and L9375;
- diagnostic cycle is applied to the L9374 current controlled channel (Qx), to collect all possible information;
- diagnostic cycle is applied also to the L9375 PWM channel (Qy);
- using information from Qx and Qy diagnostic, the microcontroller calculates the duty cycle to be imposed in order to obtain the current setpoint desired on the PWM channels of L9375.

The target of this work is to evaluate the difference between the desired current and the actual current (precision of the VCCL). The accuracy of the VCCL along different working conditions have been measured by simulating different disturbances, like battery voltage changes, load resistance change, temperature mismatches, etc.

The result of this activity is to demonstrate that it is possible to perform a low-end ABS/ESC system with only 2 current controlled channels instead of 6 required in the conventional system partitioning of the ABS/ESC control unit.

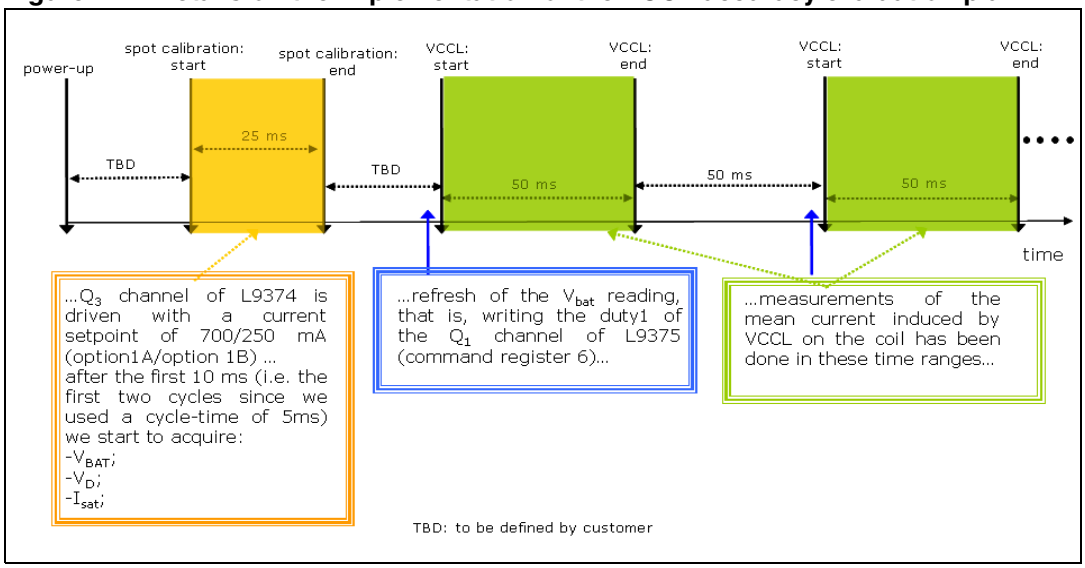
Figure 3. Block diagram of the VCCL



Figures *4* and *5* describe some details regarding the implementation of the evaluation plan conceived to quantify the VCCL accuracy. First of all, after the power-up of the microcontroller and of the L9374-L9375, a spot calibration on the Q3 channel of L9374 is

done for about 25 ms. During this time, the Q3 channel is driven in order to energize the corresponding coil mounted on the INLET valve head of the hydraulic modulator used in our tests. Two current setpoints have been explored for the spot calibration on Q3 channel: 700 mA (option 1A) and 250 mA (option 1B). While the first current setpoint is enough to close the INLET valve the last isn't. Therefore, the option 1A shows as drawback the need to close the INLET valve linked to the Q3 channel of L9374 for the spot calibration time. We chose a spot calibration time of 25 ms because this represents an optimal trade-off, taking into account the test operative conditions (the cycle-time used is about 5 ms), the filter time for the CNR condition of the current regulated channels of L9374 (t_{CNR} is equal to 8 ms) and the possibility to wait for a long enough transition time before to start the reading, by MISO bus of SPI, the VBAT (VD status register), VD (V_FWD status register) and ISAT (ISAT_Qx status registers) values (see *Figure 5*).

Figure 4. Details on the implementation of the VCCL accuracy evaluation plan


power-up
spot calibration: start
spot calibration: end
VCCL: start
VCCL: end
VCCL: start
VCCL: end
25 ms
TBD
TBD
50 ms
50 ms
50 ms
time
...Q3 channel of L9374 is driven with a current setpoint of 700/250 mA (option1A/option 1B) ... after the first 10 ms (i.e. the first two cycles since we used a cycle-time of 5ms) we start to acquire:
-VBAT;
-VD;
-Isat;
...refresh of the Vbat reading, that is, writing the duty1 of the Q1 channel of L9375 (command register 6)...
...measurements of the mean current induced by VCCL on the coil has been done in these time ranges...
TBD: to be defined by customer

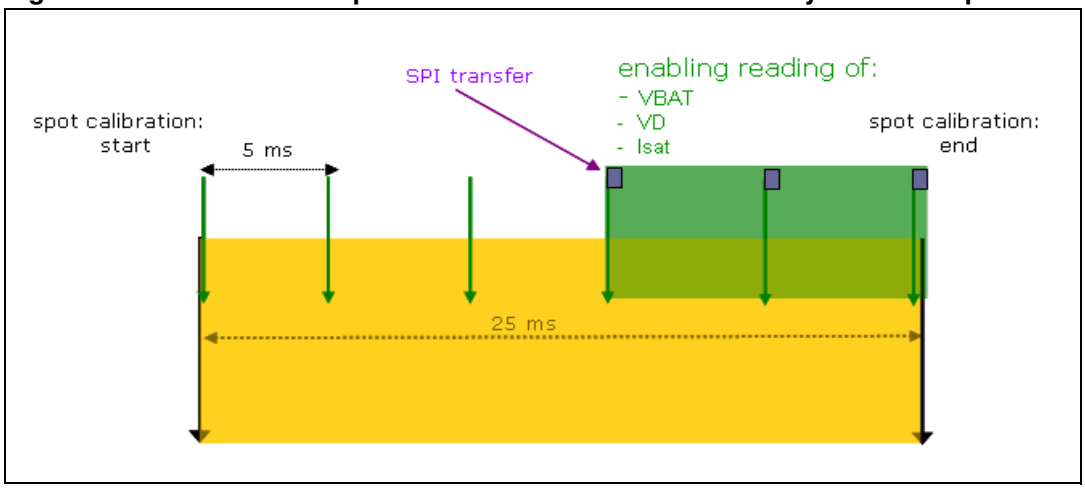
An internal common used ALU is devoted to guarantee, through the calculation of the formula (*1*), the desired accuracy (6% of error against the current setpoint) for the current control loop of the Q3 and Q4 channels of L9374. The formula (*1*) implemented in the ALU takes into account a dedicated load model. This model includes the recirculation path as well as the resistive value of the load. This value is programmable via SPI (see R_{LSPI}) while the parameters of the recirculation path and the supply voltage of the load are measured (see Rs, V_D, V_{BAT}). All these values are readable via SPI.

Equation 1

$$dc = \frac{V_D + I_{TARGET}Rs + I_{TARGET}R_{LSPI}(I_{SAT}+1)}{V_D + V_{BAT} + I_{TARGET}(Rs - Rds(on))}$$

The value of the programmed load (i.e. R_{LSPI}) is corrected during the control loop. This correction value is available via SPI (see I_{SAT}). With this algorithm a fast controller dynamic can be achieved. Starting at time zero a load error is corrected by modifying the programmed load resistor value with an integrated correction factor I_{SAT}. This function of load model correction is only available for target currents higher than 110mA. In the formula (*1*) the factor R_{LSPI} (I_{SAT} + 1) represents, in a first approximation, the real load seen by the Qx channel of L9374 into the current control loop. Anyway, for a more detailed explanation of the current control loop of the L9374 we remand to the L9374 datasheet.

Figure 5. Details on the spot calibration of the VCCL accuracy evaluation plan



During the spot calibration, once the reading window is opened (see *Figure 5*), the values of VD, VBAT, ISAT are acquired. These values after an arithmetic mean are stored in some registers of the microcontroller. Care is taken for the ISAT value because it is represented as a two complement number (see L9374 datasheet). The values $\hat{V}_D$, $\hat{V}_{BAT}$, $\hat{I}_{SAT}$ [(a)], are used into the formula (*2*) implemented by the system microcontroller in order to calculate, before to energize the coil, the right duty cycle to have a pseudo current control loop on the PWM channels of L9375. Since the L9375 does not have a real current control loop, in the formula (*2*)) there is not the Rs resistor that we can find in the formula (*1*) implemented by the ALU of L9374. However, we thought to consider a minimum resistor of 50mΩ. Furthermore, the values of the voltage drop on the free-wheeling diode (i.e. V_D) have been scaled in order to maintain a ratio of 3/4 between the voltage drop on the free-wheeling diode of the PWM channels of L9375 and the voltage drop on the free-wheeling diode of the current controlled channels of L9374.

Equation 2 $$dc = \frac{\hat{V}_D + I_{TARGET}50m\Omega + I_{TARGET}R_{LSPI}(\hat{I}_{SAT} + 1)}{\hat{V}_D + \hat{V}_{BAT} + \hat{I}_{TARGET}(50m\Omega - 200m\Omega)}$$

a. The hat on the variables indicates that they are the result of an arithmetic mean applied on the different values read via SPI once the reading window is opened (see figure5).

3 ABS/ESC: load analysis

In order to validate the VCCL approach, we used the INLET valves of the ABS/ESC 8.0 Bosch hydraulic modulator. The *Figure 6* illustrates the hydraulic modulator and the section of an INLET valve. The coil characteristics have been measured with and without the valves by means of the Hameg LCR Meter HM8018. The obtained values are:

- R = 4.65 Ohm, L = 1.6 mH (without the valve)
- R = 5.35 Ohm, L = 7.35 mH (with the valve)

Coil characteristics have been measured, also during the calibration phase of the regulated channel (i.e. Q3) of L9374, using the estimation of the load done by the L9374 through the I_{SAT} factor measurement.

Figure 6. ABS/ESC 8.0 Bosch Hydraulic modulator and INLET valve section

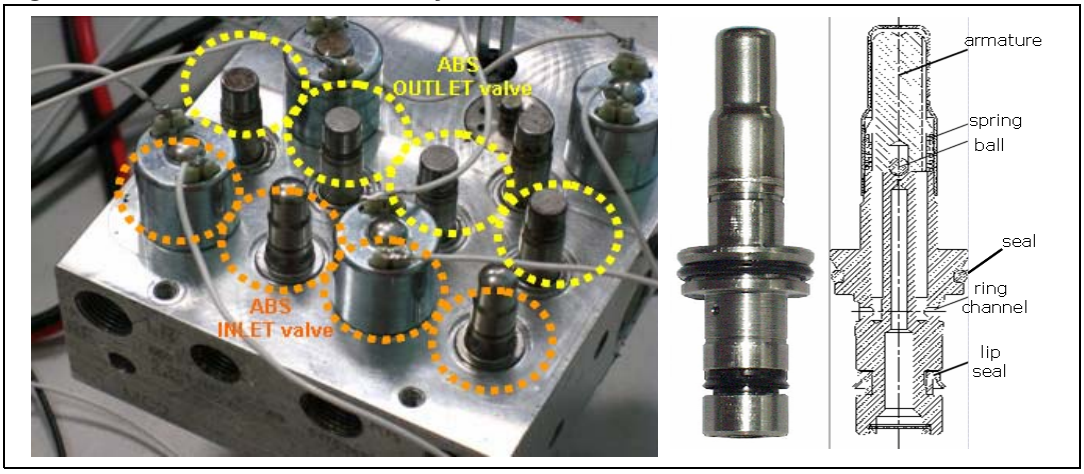


Table 1. Characterization of the load seen by the L9374 vs. the current setpoint imposed on the Q3 channel

Regulated channel current: setpoint (mA)	Load resistor seen by L9374: mean (Ohm)	Load resistor seen by L9374: std (Ohm)
250	7.17	0.03
350	6.72	0.02
450	6.68	0.02
550	6.55	0.06
650	6.52	0.04
750	6.21	0.03
850	6.23	0.06
950	6.08	0.16
1050	5.96	0.03
1150	5.6	0.16

The *Table 1* describes the results of a characterization of the load seen by the L9374 during the spot calibration versus different current setpoints. The mean and the standard deviation have been calculated on a set of 10 repeated measurements done in the same conditions (supply voltage, temperature, current setpoint, etc…).

4 Current measurement procedure: validation

The test-bench layout used to measure the current is based on the following components:

- oscilloscope LeCroy wave pro 7300A in ERES (Enhanced resolution, about 211 bit of vertical resolution) mode;
- current probe amplifier Tektronix TCPA300 (DC to 100 MHz of bandwidth, DC-gain accuracy < 1%);
- AC/DC current probe Tektronix TCP312 (Lowest Measurable Current = 1mA, Maximum Amp-Second = 50A*µs (for 1A/V range)).

Table 2. Characterization of the procedure used to measure the current into the VCCL validation tests

Regulated channel current: setpoint (mA)	Current measured on the Q3 of L9374: mean (mA)	Current measured on the Q3 of L9374: std (mA)	Percent deviation from the ideal current control accuracy of the Q3 of L9374 (%)
250	251	1	0.4
350	352	1	0.6
450	454	1	0.9
550	557	1	1.3
650	658	1	1.2
750	755	2	0.7
850	857	2	0.8
950	958	2	0.8
1050	1057	2	0.7
1150	1157	2	0.6
1250	1252	2	0.2
1350	1344	2	-0.4
1450	1462	4	0.8
1550	1566	5	1.0

The *Table 2* shows the results obtained from a preliminary characterization of the procedure adopted to measure the current into the VCCL validation tests. The results in the table *Table 2* are referred to a set of 10 repeated measurements of the current energizing the coil during the spot calibration of the L9374 and once the reading window is opened (see *Figure 5*). It is important to highlight that the measurements have been done in the same operative conditions (supply voltage, temperature, current setpoint, etc…). From an analysis of the results reported in the*Table 2*, it comes out that, in the worst case, the test bench layout used to measure the current is reliable within the limits of the 1% of accuracy.

5 VCCL accuracy evaluation

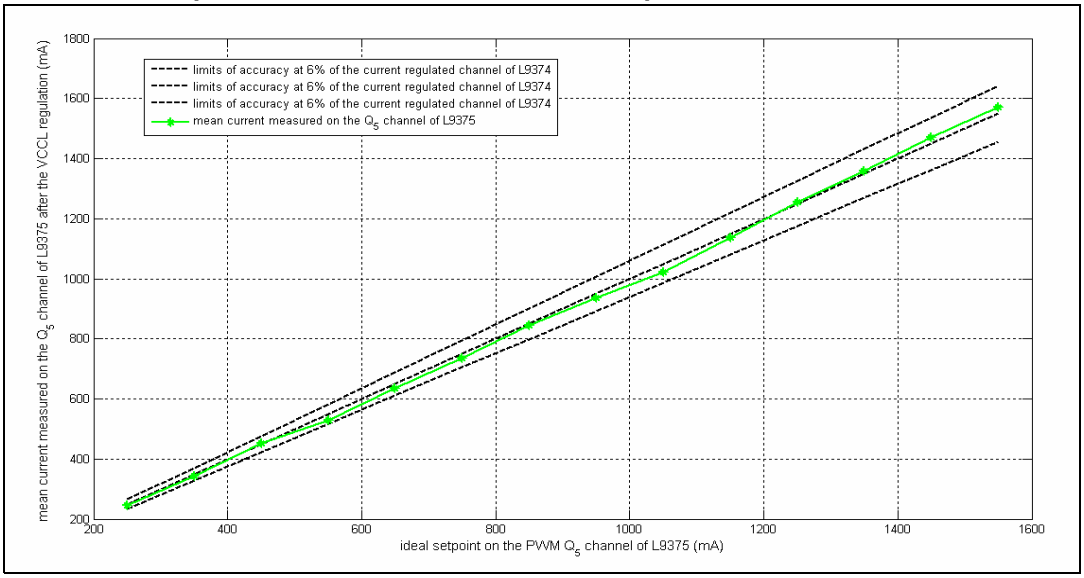
The first operative conditions in which we evaluated the performance of the VCCL are the following:

- load resistor R_{LSPI} set to 4.375 Ohm;
- supply voltage at 12 Volt both in the calibration and actuation phases;
- ideal setpoint on the Q5 channel of L9375 in [250,1550] mA;
- current setpoint on the calibration phase at 700 mA;
- 10 repeated measurements of the current mean value on the Q5 channel of L9375 after the VCCL regulation have been acquired.

Table 3. VCCL accuracy evaluation with a spot calibration having a current setpoint on the Q3 channel of L9374 equal to 700 mA

Regulated channel current: setpoint (mA)	Current measured on the Q3 of L9374: mean (mA)	Current measured on the Q3 of L9374: std (mA)	Percent deviation from the ideal current control accuracy of the Q3 of L9374 (%)
250	244	4	-2.3
350	343	1	-2
450	452	3	0.3
550	530	4	-3.7
650	635	5	-2.2
750	736	8	-1.9
850	844	3	-0.7
950	936	5	-1.4
1050	1022	8	-2.7
1150	1136	15	-1.2
1250	1257	8	0.5
1350	1360	14	0.7
1450	1472	23	1.5
1550	1572	14	1.4

Figure 7. VCCL accuracy evaluation with a spot calibration having a current setpoint on the Q3 channel of L9374 equal to 700 mA


limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
mean current measured on the Q5 channel of L9375
mean current measured on the Q5 channel of L9375 after the VCCL regulation (mA)
ideal setpoint on the PWM Q5 channel of L9375 (mA)
200
400
600
800
1000
1200
1400
1600
1800

Moreover, we tested the sensitivity of the VCCL approach in the spot calibration option 1A against power supply change. In other words, we explored the working of the VCCL when there is a mismatch between the power supply value during the spot calibration time and during the actuation phase of the VCCL on the PWM channels of L9375. The *Table 4* and the figures *8*, *9*, *10* show the results of this analysis. It comes out when there is a voltage drop going from the spot calibration on Q3 channel of L9374 to the actuation on the PWM channels of L9375, the performance of VCCL seem to be less satisfactory than the performance in "ideal" conditions shown before (see *Table 3* and *Figure 7*) and the performance when there is a voltage increase going from the spot calibration to the actuation phase. Anyway, discarding the results referred to the ideal current setpoint of 1350 mA, also in these operative conditions, that is, voltage drop going from the spot calibration to the actuation phase, the VCCL performance are within the 6% accuracy cone of the current controlled channels of L9374 (see figures *8*, *9*, *10*).

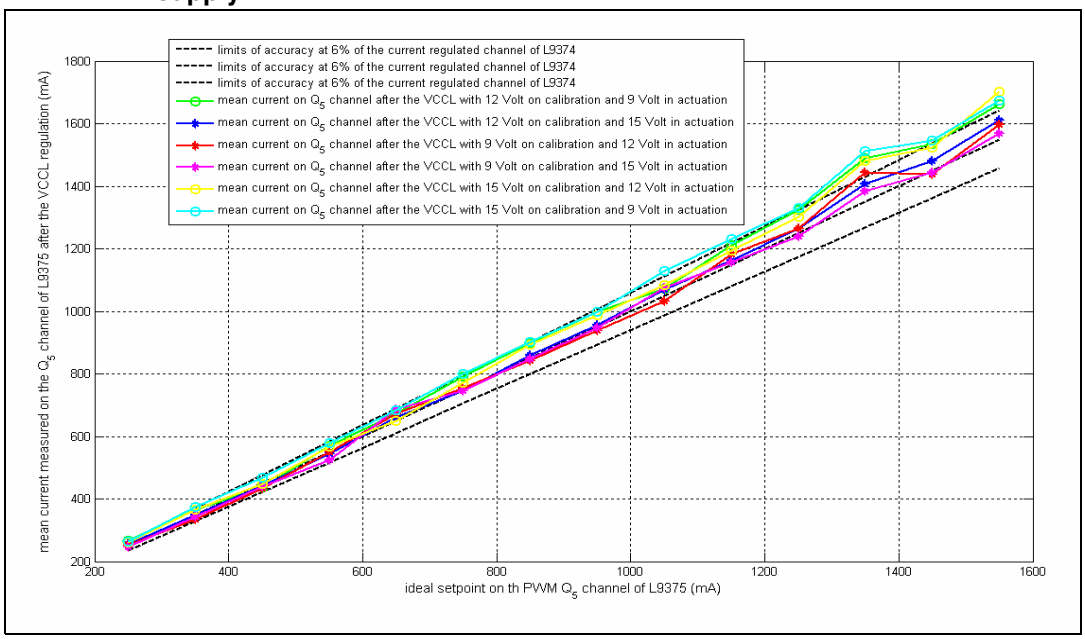
The *Table 4* shows the VCCL accuracy evaluation in option 1A spot calibration versus power supply mismatch between the power supply value during the spot calibration time and during the actuation phase of the VCCL on the PWM channels of L9375.

Table 4. VCCL accuracy evaluation in option 1A spot calibration versus power supply

Ideal current setpoint on Q5 channel of L9375 (mA)	12 V in cal. phase 9 V in actuation:		12 V in cal. phase 15 V in actuation:		9 V in cal. phase 12 V in actuation:		9 V in cal. phase 15 V in actuation:		15 V in cal. phase 15 V in actuation:		15 V in cal. phase 9 V in actuation:	
	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)
250	266	6.4	254	1.6	252	0.8	247	-1.2	260	4	265	6
350	366	4.6	349	-0.3	334	-4.6	344	-1.7	366	4.6	375	7.1
450	436	-3.1	442	-1.8	435	-3.3	441	-2	448	-0.4	467	3.8
550	571	3.8	544	-1.1	550	0	525	-4.5	567	3.1	580	5.5
650	672	3.4	661	1.7	672	3.4	687	5.7	650	0	685	5.4
750	791	5.5	747	-0.4	754	0.5	746	-0.5	771	2.8	799	6.5
850	899	5.8	860	1.2	843	-0.8	849	-0.1	895	5.3	903	6.2
950	1000	5.3	955	0.5	939	-1.2	948	-0.2	988	4	998	5.1
1050	1073	2.2	1069	1.8	1032	-1.7	1074	2.3	1085	3.3	1128	7.4
1150	1211	5.3	1163	1.1	1183	2.9	1158	0.7	1193	3.7	1232	7.1
1250	1326	6.1	1266	1.3	1266	1.3	1241	-0.7	1302	4.2	1331	6.5
1350	1488	10.2	1407	4.2	1444	7	1384	2.5	1482	9.8	1513	12.1
1450	1534	5.8	1481	2.1	1439	-0.8	1444	-0.4	1524	5.1	1547	6.7
1550	1662	7.2	1610	3.9	1597	3	1568	1.2	1702	9.8	1675	8.1

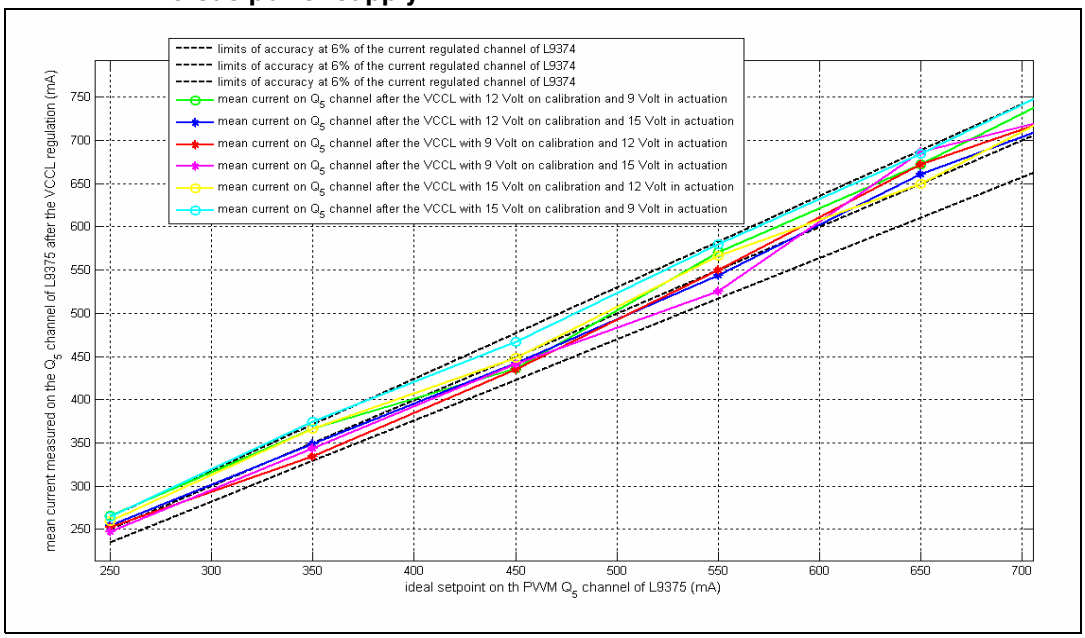
The *Figure 8* shows VCCL accuracy evaluation in option 1A spot calibration versus power supply mismatch between the power supply value during the spot calibration time and during the actuation phase of the VCCL on the PWM channels of L9375.

Figure 8. VCCL accuracy evaluation in option 1A spot calibration versus power supply


limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 9 Volt in actuation
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 9 Volt in actuation
mean current measured on the Q5 channel of L9375 after the VCCL regulation (mA)
ideal setpoint on th PWM Q5 channel of L9375 (mA)
200
400
600
800
1000
1200
1400
1600
1800

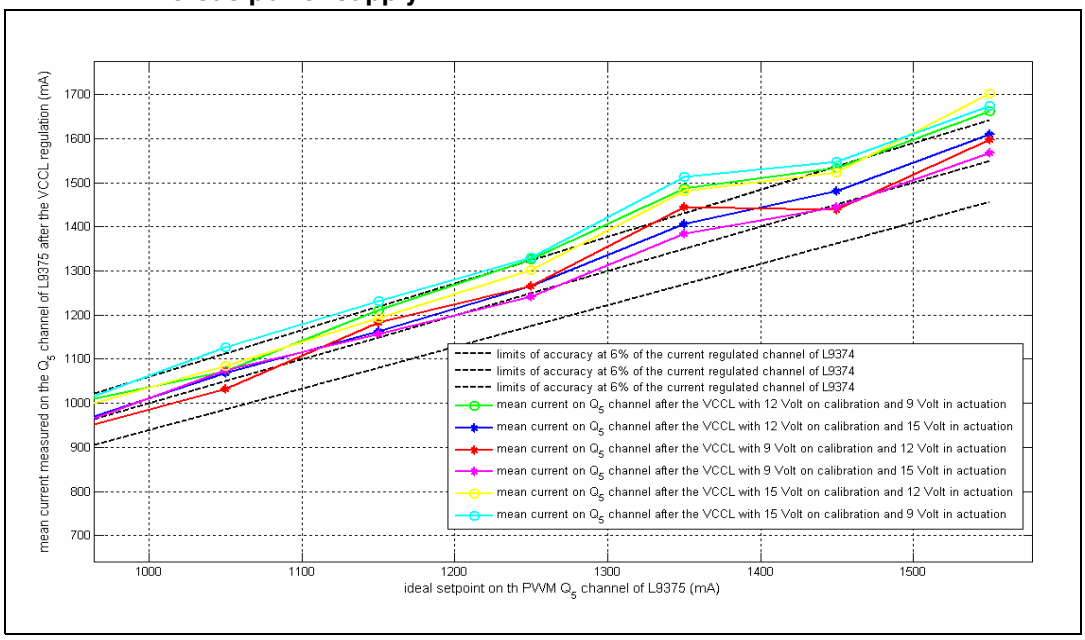
The *Figure 9* shows the detail of the VCCL accuracy evaluation in option 1A spot calibration versus power supply mismatch between the power supply value during the spot calibration time and during the actuation phase of the VCCL on the PWM channels of L9375.

Figure 9. Detail of the VCCL accuracy evaluation in option 1A spot calibration versus power supply


limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 9 Volt in actuation
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 9 Volt in actuation
mean current measured on the Q5 channel of L9375 after the VCCL regulation (mA)
ideal setpoint on th PWM Q5 channel of L9375 (mA)
250
300
350
400
450
500
550
600
650
700
750

The *Figure 10* shows the detail of the VCCL accuracy evaluation in option 1A spot calibration versus power supply mismatch between the power supply value during the spot calibration time and during the actuation phase of the VCCL on the PWM channels of L9375.

Figure 10. Detail of the VCCL accuracy evaluation in option 1A spot calibration versus power supply


mean current measured on the Q5 channel of L9375 after the VCCL regulation (mA)
ideal setpoint on th PWM Q5 channel of L9375 (mA)
limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 9 Volt in actuation
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 9 Volt in actuation

The second operative conditions in which we evaluated the performance of the VCCL are the following:

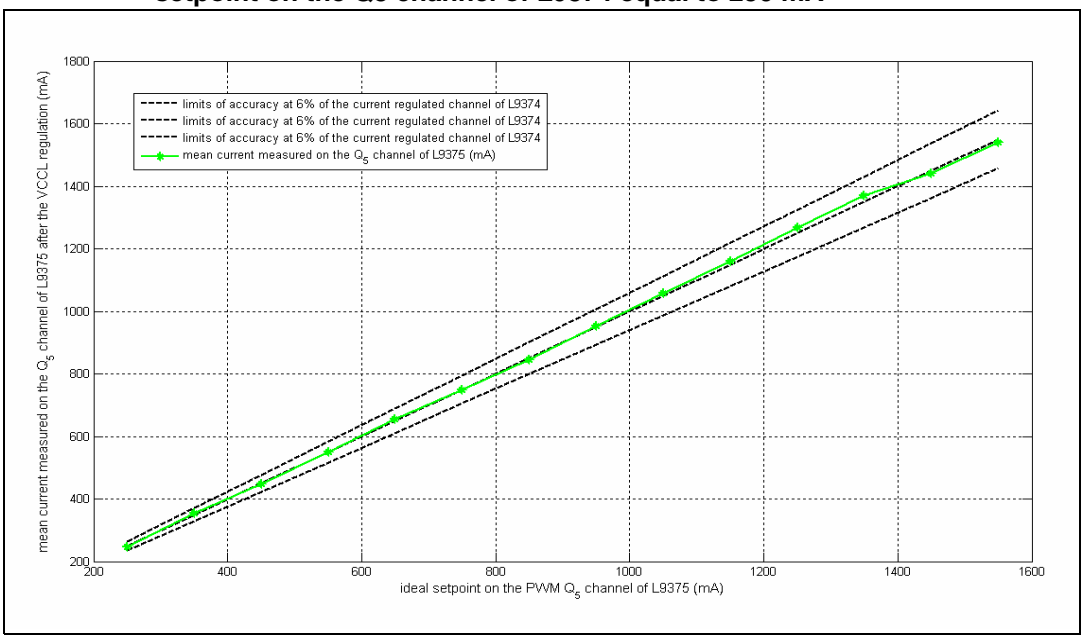
- load resistor RLSPI set to 4.375 Ohm;
- supply voltage at 12 Volt both in the calibration and actuation phases;
- ideal setpoint on the Q5 channel of L9375 in [250,1550] mA;
- current setpoint on the calibration phase at 250 mA;
- 10 repeated measurements of the current mean value on the Q5 channel of L9375 after the VCCL regulation have been acquired.

Also in this case we analyzed the sensitivity of the VCCL approach against power supply mismatches. In order to improve the VCCL performance we implemented a load change model inspired to the load characterization shown in the *Section 5*. Basically, if this load change model is not implemented the performance of the VCCL approach, in the calibration option 1B, are less satisfactory than the VCCL performance obtained with the option 1A. The main advantage of the VCCL option 1B approach is that the current required during the spot calibration is not enough to close the INLET valve. So the customer could repeat periodically the same calibration procedure also taking into account to change the current setpoint of the spot calibration always keeping the current value under the minimum value that is enough to close the INLET valve (e.g. 500-550mA mA for the INLET valve of the 8.0 Bosch ABS/ESC control unit hydraulic modulator).

Table 5. VCCL accuracy evaluation with a spot calibration having a current setpoint on the Q3 channel of L9374 equal to 250 mA

Ideal current setpoint on Q5 channel of L9375 (mA)	Current measured on the Q5 of L9375: mean (mA)	Current measured on the Q5 of L9375: std (mA)	Percent deviation from the ideal current setpoint on Q5 channel of L9375 (%)
250	248	2	-0.8
350	356	4	1.7
450	447	7	-0.7
550	549	4	-0.2
650	654	7	0.6
750	749	9	-0.1
850	846	7	-0.5
950	954	6	0.4
1050	1058	2	0.8
1150	1159	11	0.8
1250	1267	12	1.4
1350	1370	10	1.5
1450	1442	13	-0.6
1550	1540	6	-0.6

Figure 11. VCCL accuracy evaluation with a spot calibration having a current setpoint on the Q3 channel of L9374 equal to 250 mA


limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
mean current measured on the Q5 channel of L9375 (mA)
mean current measured on the Q5 channel of L9375 after the VCCL regulation (mA)
ideal setpoint on the PWM Q5 channel of L9375 (mA)
200
400
600
800
1000
1200
1400
1600
1800

The *Table 5* and the related *Figure 11* describe the behavior of the VVCL approach in the spot calibration option 1B. On the other hand, the *Table 6* and the figures *12*, *13*, *14* show the results of the sensitivity analysis of the approach against power supply mismatches

between the power supply values during the spot calibration and during the actuation phase. Also in this case, it comes out when there is a voltage drop going from the calibration phase to the actuation phase, the performance of the VCCL approach decreases. Anyway, discarding the results referred to some ideal current setpoints, also in these operative conditions, that is, voltage drop going from the spot calibration to the actuation phase, the VCCL shows performance that are basically within the 6% accuracy cone of the current controlled channels of L9374 (see figures *8*, *9*, *10*).

At last, we have simulated a temperature mismatch between the coil associated to the Q3 channel of L9374 and the coil associated to the Q5 channel of L9375. Using some 30W 0.05 Ohm 1% precision resistors, we added a resistor of 0.4 Ohm in series either at the load coil corresponding to the PWM channel of L9375 or at the load coil corresponding to the Q3 channel of L9374. Taking into account the formula (*3*) of the resistance of the chopper versus the temperature and the initial value of the load resistor $R_{initial}$ = 4.65 Ohm (see *Section 5*), it is simple to verify that the resistor of 0.4 Ohm in series corresponds to a simulation of temperature gradient of 20°.

Equation 3 $R_{last} = R_{initial}(1 + 0.004\Delta T)$

The tables *7*, *8*, *9*, *10* and the figures *15*, *16* show the results of this analysis. Also in this case, it comes out that the accuracy of the VCCL maintains itself within the 6% accuracy cone of the current controlled channels of L9374.

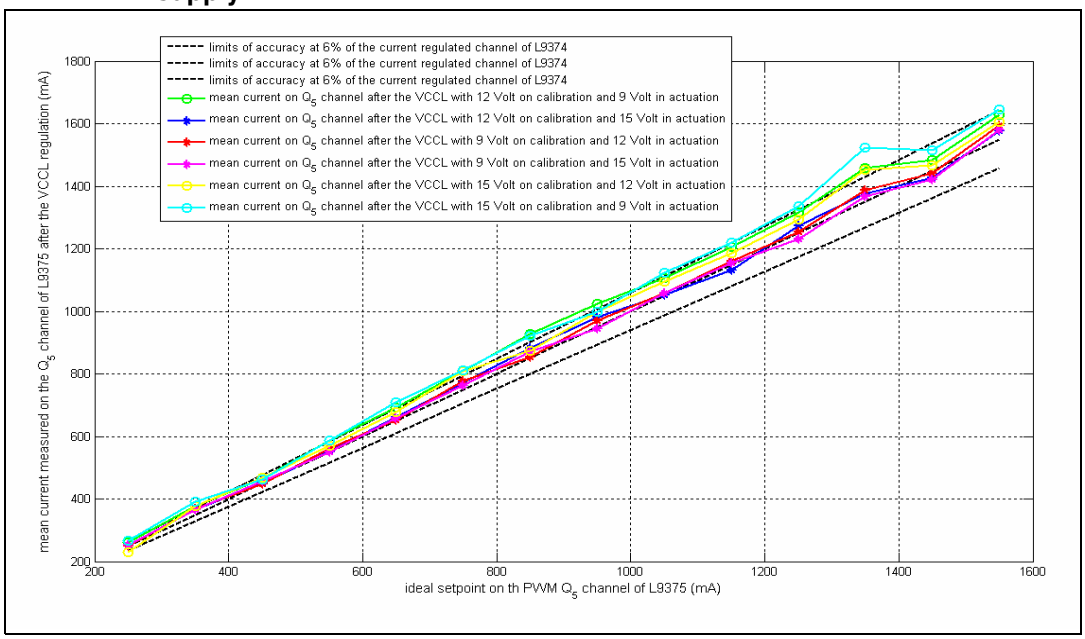
The *Table 6* shows VCCL accuracy evaluation in option 1B spot calibration versus power supply mismatch between the power supply value during the spot calibration time and during the actuation phase of the VCCL on the PWM channels of L9375.

Table 6. VCCL accuracy evaluation in option 1B spot calibration versus power supply

Ideal current setpoint on Q5 channel of L9375 (mA)	12 V in cal. phase 9 V in actuation:		12 V in cal. phase 15 V in actuation:		9 V in cal. phase 12 V in actuation:		9 V in cal. phase 15 V in actuation:		15 V in cal. phase 15 V in actuation:		15 V in cal. phase 9 V in actuation:	
	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)	mean current on Q5 of L9375 (mA)	percent deviation vs. setpoint (%)
250	262	4.8	253	1.2	250	0	253	1.2	229	-8.4	268	7.2
350	378	8	367	4.9	368	5.1	365	4.3	377	7.7	392	12
450	466	3.6	451	0.2	449	-0.2	457	1.6	467	3.8	462	2.7
550	587	6.7	554	0.7	561	2	549	-0.2	571	3.8	588	6.9
650	691	6.3	661	1.7	653	0.5	657	1.1	679	4.5	710	9.2
750	809	7.9	772	2.9	777	3.6	764	1.9	809	7.9	811	8.1
850	928	9.2	883	3.9	854	0.5	871	2.5	873	2.7	921	8.4
950	1024	7.8	982	3.4	970	2.1	946	-0.4	1000	5.3	998	5.1
1050	1107	5.4	1052	0.2	1059	0.9	1059	0.9	1096	4.4	1124	7
1150	1205	4.8	1133	-1.5	1160	0.9	1154	0.3	1187	3.2	1220	6.1
1250	1316	5.3	1273	1.8	1253	0.2	1230	-1.6	1293	3.4	1337	7
1350	1457	7.9	1377	2	1388	2.8	1367	1.3	1453	7.6	1524	12.9
1450	1484	2.3	1426	-1.7	1442	-0.6	1420	-2.1	1467	1.2	1516	4.6
1550	1628	5	1578	1.8	1594	2.8	1581	2	1607	3.7	1645	6.1

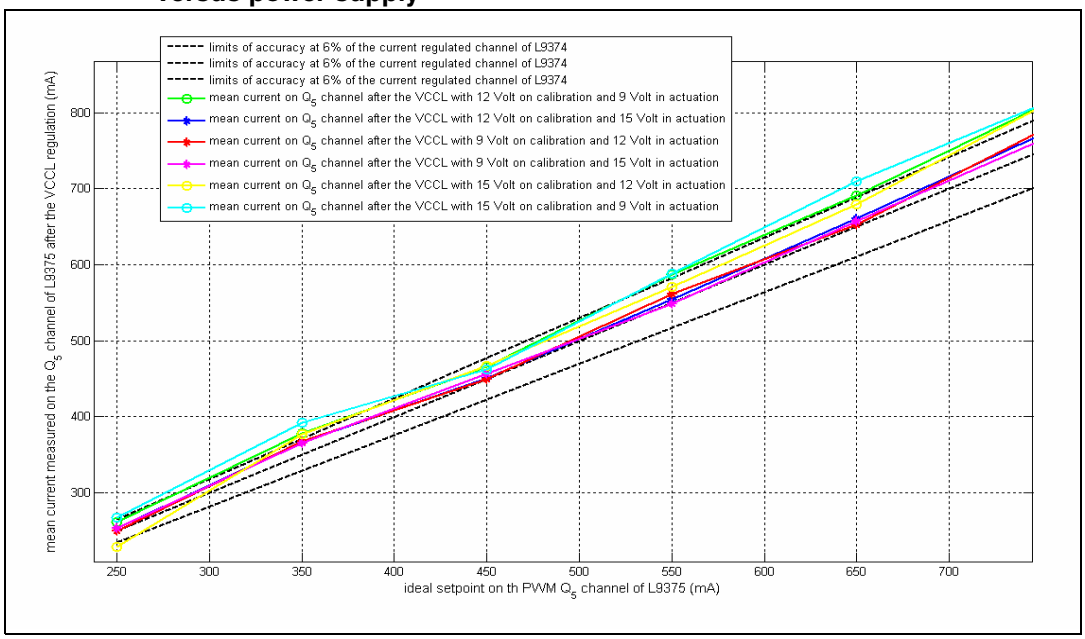
The *Figure 12* shows VCCL accuracy evaluation in option 1B spot calibration versus power supply mismatch between the power supply value during the spot calibration time and during the actuation phase of the VCCL on the PWM channels of L9375.

Figure 12. VCCL accuracy evaluation in option 1B spot calibration versus power supply


limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 9 Volt in actuation
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 9 Volt in actuation
mean current measured on the Q5 channel of L9375 after the VCCL regulation (mA)
ideal setpoint on th PWM Q5 channel of L9375 (mA)
200
400
600
800
1000
1200
1400
1600
1800

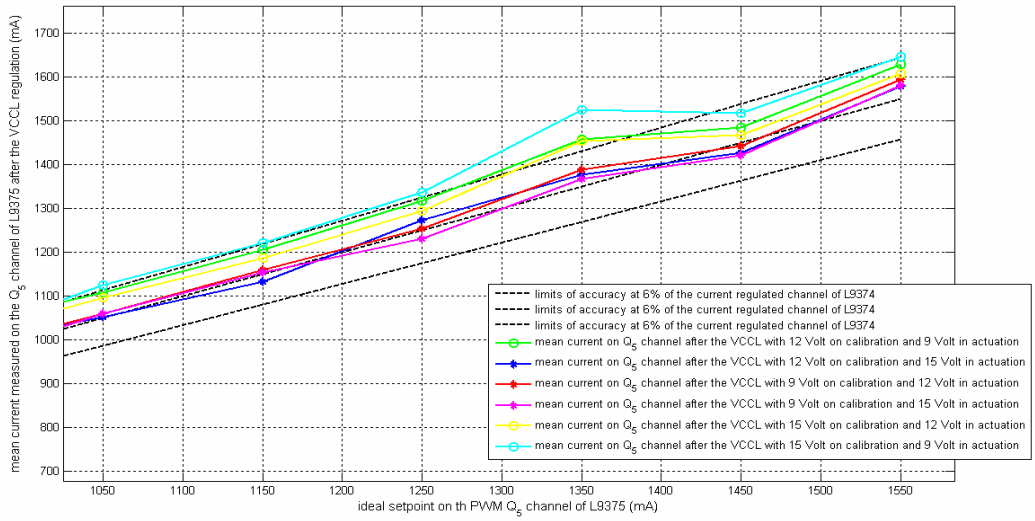
The *Figure 13* shows the detail of the VCCL accuracy evaluation in option 1B spot calibration versus power supply mismatch between the power supply value during the spot calibration time and during the actuation phase of the VCCL on the PWM channels of L9375.

Figure 13. Detail of the VCCL accuracy evaluation in option 1B spot calibration versus power supply


limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 9 Volt in actuation
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 9 Volt in actuation
mean current measured on the Q5 channel of L9375 after the VCCL regulation (mA)
ideal setpoint on th PWM Q5 channel of L9375 (mA)
250
300
350
400
450
500
550
600
650
700
300
400
500
600
700
800

The *Figure 14* shows the detail of the VCCL accuracy evaluation in option 1B spot calibration versus power supply mismatch between the power supply value during the spot calibration time and during the actuation phase of the VCCL on the PWM channels of L9375.

Figure 14. Detail of the VCCL accuracy evaluation in option 1B spot calibration versus power supply


mean current measured on the Q5 channel of L9375 after the VCCL regulation (mA)
ideal setpoint on th PWM Q5 channel of L9375 (mA)
limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 9 Volt in actuation
mean current on Q5 channel after the VCCL with 12 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 9 Volt on calibration and 15 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 12 Volt in actuation
mean current on Q5 channel after the VCCL with 15 Volt on calibration and 9 Volt in actuation

The *Table 7* shows the VCCL accuracy evaluation in option 1A when a temperature mismatch of 20° is simulated. A precision resistor of 0.4 Ohm is added in series at the coil corresponding to the Q5 channel of L9375.

Table 7. VCCL accuracy evaluation in option 1A when a temperature mismatch of 20° is simulated (Q5 channel of L9375)

Ideal setpoint (mA)	Mean (mA)	Max percent error measured on the Q5 channel of L9375 after the VCCL (%)
250	240	-4
350	347	-0.9
450	431	-4.2
550	527	-4.2
650	627	-3.5
750	721	-3.9
850	828	-2.6
950	999	5.2
1050	1004	-4.4
1150	1094	-4.9
1250	1202	-3.8
1350	1341	-0.7
1450	1408	-2.9
1550	1530	-1.3

The *Table 8* shows the VCCL accuracy evaluation in option 1A when a temperature mismatch of 20° is simulated. A precision resistor of 0.4 Ohm is added in series at the coil corresponding to the Q3 channel of L9374.

Table 8. VCCL accuracy evaluation in option 1A when a temperature mismatch of 20° is simulated (Q3 channel of L9375)

Ideal setpoint (mA)	Mean (mA)	Max percent error measured on the Q5 channel of L9375 after the VCCL (%)
250	248	-0.8
350	346	-1.1
450	423	-6
550	520	-5.5
650	650	0
750	747	-0.4
850	855	0.6
950	971	2.2
1050	1053	0.3
1150	1165	1.3
1250	1274	1.9
1350	1404	4
1450	1507	3.9
1550	1622	4.6

The *Table 9* shows the VCCL accuracy evaluation in option 1B when a temperature mismatch of 20° is simulated. A precision resistor of 0.4 Ohm is added in series at the coil corresponding to the Q5 channel of L9375.

Table 9. VCCL accuracy evaluation in option 1B when a temperature mismatch of 20° is simulated (Q5 channel of L9375)

Ideal setpoint (mA)	Mean (mA)	Max percent error measured on the Q5 channel of L9375 after the VCCL (%)
250	254	1.7
350	358	2.4
450	442	-1.8
550	549	-0.2
650	633	-2.6
750	746	-0.5
850	845	-0.6
950	937	-1.4
1050	1032	-1.7
1150	1132	-1.6
1250	1249	-0.1
1350	1365	1.1
1450	1442	-0.6
1550	1550	0

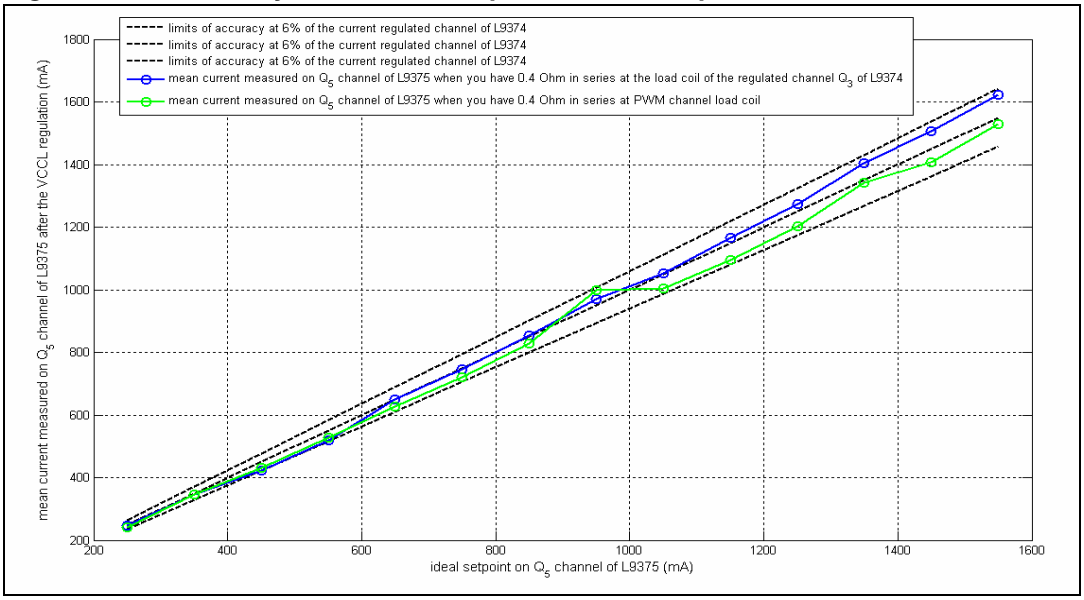
The *Table 10* shows the VCCL accuracy evaluation in option 1B when a temperature mismatch of 20° is simulated. A precision resistor of 0.4 Ohm is added in series at the coil corresponding to the Q3 channel of L9374.

Table 10. VCCL accuracy evaluation in option 1B when a temperature mismatch of 20° is simulated (Q3 channel of L9375)

Ideal setpoint (mA)	Mean (mA)	Max percent error measured on the Q5 channel of L9375 after the VCCL (%)
250	256	2.4
350	367	4.9
450	462	2.7
550	573	4.2
650	679	4.5
750	778	3.7
850	885	4.1
950	994	4.6
1050	1092	4
1150	1218	5.9
1250	1316	5.3
1350	1469	8.8
1450	1475	1.7
1550	1628	5

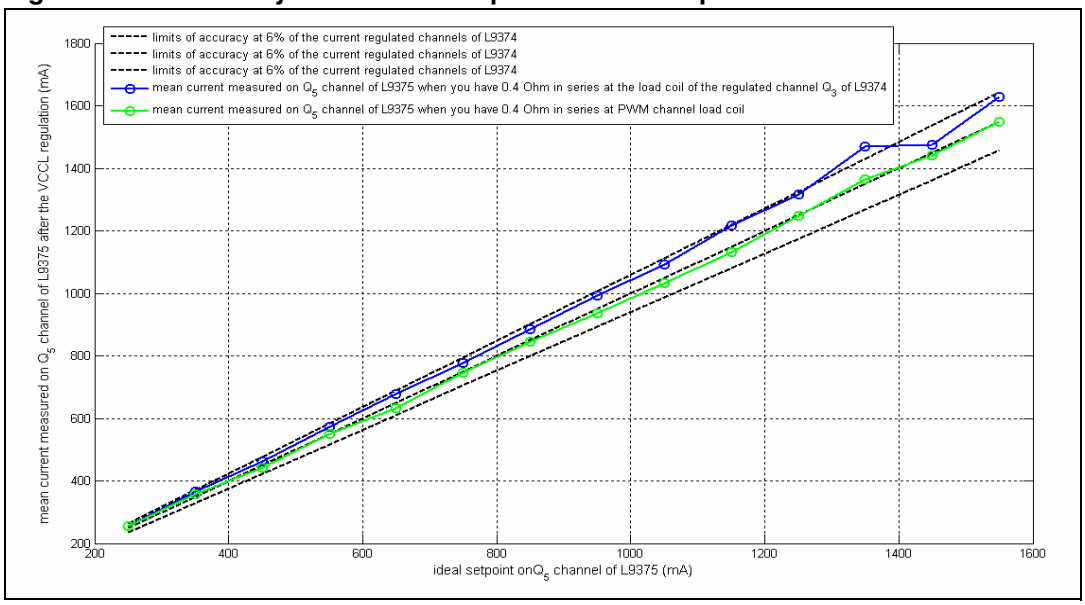
The *Figure 15* shows the sensitivity versus coil temperature in the option 1A VCCL, results with a mismatch of 0.4 Ohm between the load resistor of the Q3 channel of L9374 and the Q5 channel of L9375

Figure 15. Sensitivity versus coil temperature in the option 1A VCCL


limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
limits of accuracy at 6% of the current regulated channel of L9374
mean current measured on Qs channel of L9375 when you have 0.4 Ohm in series at the load coil of the regulated channel Q3 of L9374
mean current measured on Qs channel of L9375 when you have 0.4 Ohm in series at PWM channel load coil
mean current measured on Qs channel of L9375 after the VCCL regulation (mA)
ideal setpoint on Qs channel of L9375 (mA)
200
400
600
800
1000
1200
1400
1600
1800

The *Figure 16* shows the sensitivity versus coil temperature in the option 1B VCCL, results with a mismatch of 0.4 Ohm between the load resistor of the Q3 channel of L9374 and the Q5 channel of L9375

Figure 16. Sensitivity versus coil temperature in the option 1B VCCL


limits of accuracy at 6% of the current regulated channels of L9374
limits of accuracy at 6% of the current regulated channels of L9374
limits of accuracy at 6% of the current regulated channels of L9374
mean current measured on Q5 channel of L9375 when you have 0.4 Ohm in series at the load coil of the regulated channel Q3 of L9374
mean current measured on Q5 channel of L9375 when you have 0.4 Ohm in series at PWM channel load coil
mean current measured on Q5 channel of L9375 after the VCCL regulation (mA)
ideal setpoint onQ5 channel of L9375 (mA)
200
400
600
800
1000
1200
1400
1600
1800

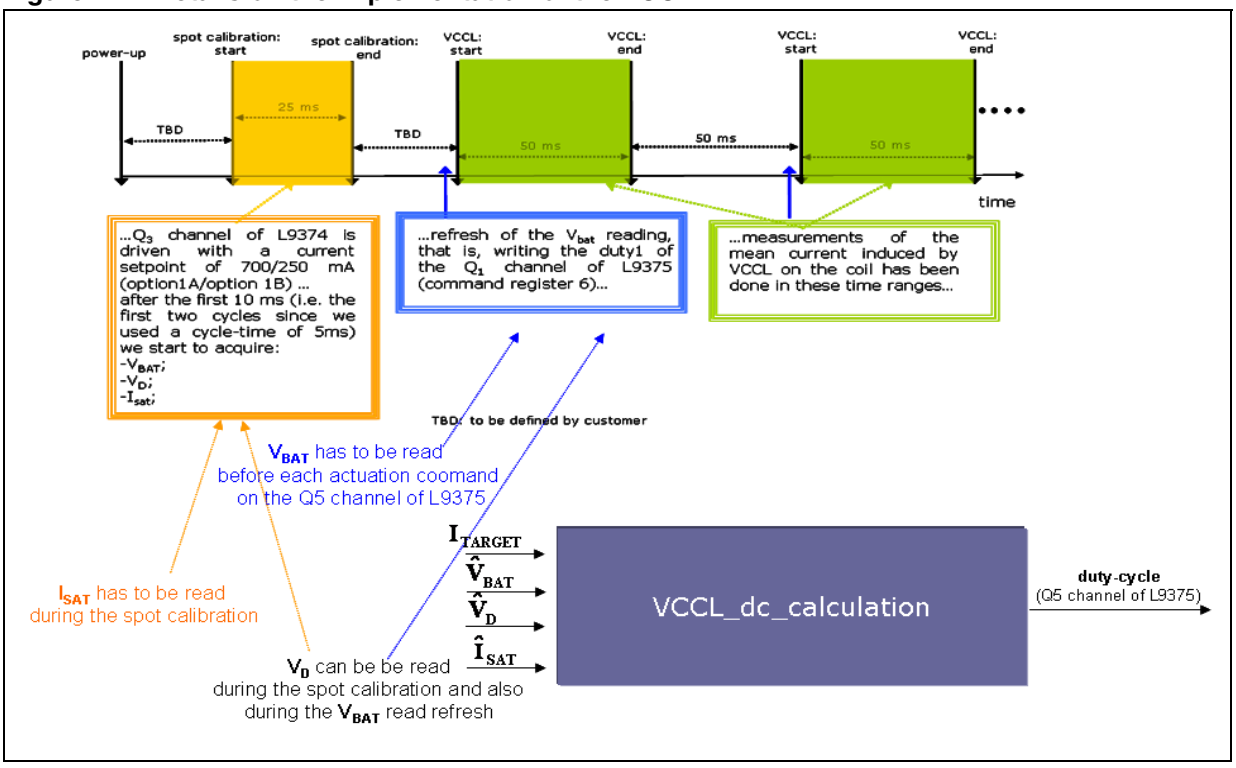
6 VCCL: computational burden evaluation

The *Figure 17* describes, in a more detail, the implementation of the VCCL. During the spot calibration once there is the enabling of the reading window (see *Figure 5*), the values of VD, VBAT, ISAT are acquired. Before to start the actuation on the Q5 channel of L9375, we update the reading of the VBAT by means of the setting of the command register 6 of the L9375, that is, we set the duty1 of the Q1 channel of L9375. These values are stored and averaged. The arithmetic means are the inputs of the main function of the VCCL: VCCL_dc_calculation. This function calculates the duty-cycle value according to the formula (*2*). This duty-cycle value is used to set the command registers of the Q5 channel of L9375 in order to carry out the VCCL.

From a point of view of the computation load, we analyzed the cost of the VCCL_dc_calculation function call for two different microcontroller architectures (ST10F252M and ST-Pictus) by two different approaches:

- Toggling a pin before and after the VCCL_dc_calculation function call;
- Counting the number of instruction-cycles.

Figure 17. Details on the implementation of the VCCL


power-up
spot calibration: start
spot calibration: end
VCCL: start
VCCL: end
VCCL: start
VCCL: end
25 ms
TBD
TBD
50 ms
50 ms
50 ms
time
...Q3 channel of L9374 is driven with a current setpoint of 700/250 mA (option1A/option 1B) ... after the first 10 ms (i.e. the first two cycles since we used a cycle-time of 5ms) we start to acquire:
-VBAT;
-VD;
-Isat;
...refresh of the Vbat reading, that is, writing the duty1 of the Q1 channel of L9375 (command register 6)...
...measurements of the mean current induced by VCCL on the coil has been done in these time ranges...
TBD: to be defined by customer
VBAT has to be read before each actuation coomand on the Q5 channel of L9375
ISAT has to be read during the spot calibration
VD can be be read during the spot calibration and also during the VBAT read refresh
ITARGET
V̂BAT
V̂D
Î SAT
VCCL_dc_calculation
duty-cycle
(Q5 channel of L9375)

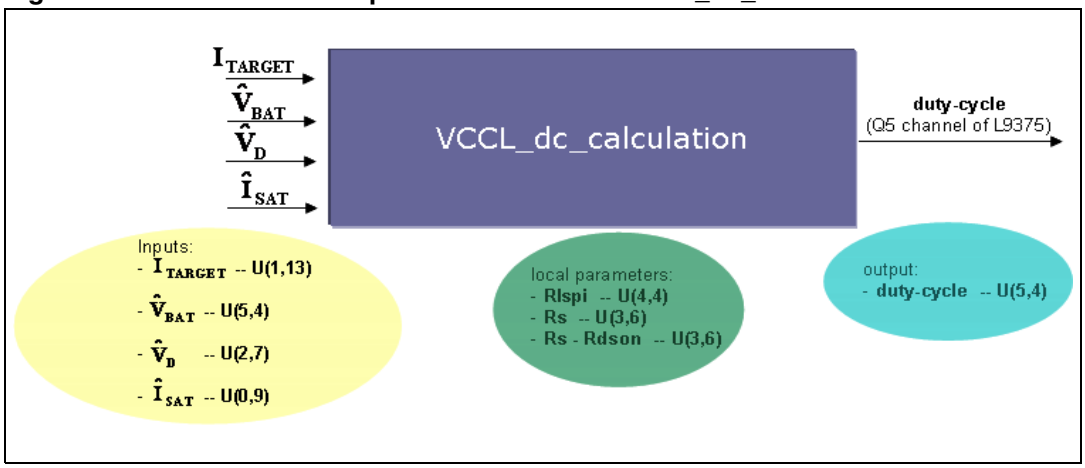
Toggling a pin before and after the VCCL_dc_calculation function call, we observed that the cost of the VCCL_dc_calculation function call is 27µs for the ST10F252M and 4 µs for the ST-Pictus, respectively. Moreover, counting the number of instruction-cycles, we estimated about 500 instruction-cycle for each VCCL_dc_calculation function call on a microcontroller architecture similar to ST10 one and we estimated about 250 instruction-cycle for each VCCL_dc_calculation function call on a microcontroller architecture similar to ST-Pictus one. Considering that for the ST10 microcontroller architecture there is a correspondence of 2 clock-hits for each instruction-cycle, the VCCL_dc_calculation function call costs about 1000

clock-hits, that is, about 25 µs for the ST10F252M clock-frequency at 40 MHz. On the other hand, considering that for ST-Pictus microcontroller architecture there is a correspondence of 1 clock-hit for each instruction-cycle, the VCCL_dc_calculation function call costs about 250 clock-hit, that is, about 3.9 µs for the clock-frequency at 64 MHz. Both the estimation based on the counting of the instruction-cycles number confirm the results measured by the oscilloscope via toggling mode approach. Finally, taking into account that the worst case is when you have to drive all the 4 PWM channels of the L9375 setting two different duty-cycle values (two different current set-points) into the cycle-time, this means 8 different VCCL_dc_calculation function calls for each cycle-time, that is, about 200 µs for the STF252M and 32 µs for the ST-Pictus, respectively.

7 VCCL: fixed point arithmetic

The *Figure 18* describes the implementation of the VCCL_dc_calculation function. The averaged values of $\hat{V}_D$, $\hat{V}_{BAT}$, $\hat{I}_{SAT}$ with the current setpoint I_{TARGET} are the inputs of the VCCL_dc_calculation function. The local parameters Rs and Rdson are equal to 50 mΩ and 200 mΩ, respectively.

Figure 18. Details on the implementation of the VCCL_dc_calculation function



The inputs, outputs and the local parameters of the VCCL_dc_calculation function are interpreted as unsigned fixed point rationals. Even though, $\hat{I}_{SAT}$ is represented on the status registers 8 and 9 of the L9374 as a two complement number, for a sake of simplicity, we preferred to consider $\hat{I}_{SAT}$ as an U(0,9) number. If the sign bit, the MSB of the data bits string is low I read the least significant 9 bits as an U(0,9), otherwise if the sign bit if the sign bit is high I read the least significant 9 bits as an U(0,9) after a not of the word plus 1. Furthermore, I read I_{TARGET} as an U(1,13). It is possible to demonstrate that this interpretation of the current setpoint (i.e. I_{TARGET}) implies an error in data representation of 0.5%.

The steps of the VCCL_dc_calculation function call are the following:

- $(1+I_{sat})$ - U(1,9)
- I_{TARGET}*Rs - U(4,19)
- I_{TARGET}*Rs>>2 - U(4,17)
- Num1 = I_{TARGET}*Rs + Vd<<10 -- U(5,17)
- Num2 = (Rlspi*(1+Isat))>>2 - U(5,11)
- Num2 = I_{TARGET}*Rlspi*(1+Isat) - U(6,24)
- NumEff = Num1 + Num2>>7 -- U(7,17)
- Den1 = Vd + Vbat<<3 -- U(6,7)
- Den2 = I_{TARGET}*(Rs-Rsdson) -- U(4,19)
- DenEff = Den1<<6 + Den2>>6 - U(7,13)
- NumEff = NumEff>>4 -- U(7,13)
- NumEff = NumEff*100
- dc = (NumEff<<4)/DenEff … I read this as an U(5,4)

The local variables listed before are unsigned integer at 32 bits. After the duty-cycle calculation, you have only to set the command registers (i.e. 10, 11, 12, 13) of the PWM channels of L9375 you want to drive as there was a current control loop.

At last, we reassume, in the *Table 11*, the results of an off-line characterization of the VCCL_dc_calculation function for different values of the current setpoint and of the Isat factor.

Table 11. Analysis of the error propagation in the VCCL_dc_calculation function call versus different Isat value and current setpoints

Isat value	Floating point calculation of duty cycle	Fixed point calculation of duty cycle	Percent error between fixed and floating point calculation
Setpoint 250 mA			
0.1	15.7	15.5	1.3
0.3	17.52	17.3125	1.2
0.5	19.355	19.1875	0.9
-0.1	13.853	13.6875	1.2
-0.3	12.02	11.81	1.7
-0.5	10.185	10	1.8
Setpoint 350 mA			
0.1	19.91	19.56	1.8
0.3	22.48	22.12	1.6
0.5	25.05	24.625	1.7
-0.1	17.338	17	1.9
-0.3	14.767	14.4375	2.2
-0.5	12.196	11.9375	2.1
Setpoint 450 mA			
0.1	24.147	23.75	1.6
0.3	27.458	27.06	1.4
0.5	30.769	30.31	1.5
-0.1	20.835	20.4375	1.9
-0.3	17.524	17.1875	1.9
-0.5	14.213	13.875	2.4
Setpoint 550 mA			
0.1	27.96	28.06	-0.4
0.3	29.98	30.06	-0.3
0.5	36.06	36.18	-0.3
-0.1	23.9	24	-0.4

Table 11. Analysis of the error propagation in the VCCL_dc_calculation function call versus different Isat value and current setpoints (continued)

Isat value	Floating point calculation of duty cycle	Fixed point calculation of duty cycle	Percent error between fixed and floating point calculation
-0.3	19.85	19.93	-0.4
-0.5	15.79	15.87	-0.5
Setpoint 650 mA			
0.1	32.658	32.3125	1.1
0.3	37.455	37.0625	1.0
0.5	42.253	41.875	0.9
-0.1	27.861	27.5	1.3
-0.3	23.063	22.6875	1.6
-0.5	18.265	17.875	2.1
Setpoint 750 mA			
0.1	36.933	36.5625	1.0
0.3	42.477	42.125	0.8
0.5	48.02	47.625	0.8
-0.1	31.389	31	1.2
-0.3	25.845	25.4375	1.6
-0.5	20.3	19.875	2.1
Setpoint 850 mA			
0.1	40.55	40.81	-0.6
0.3	46.85	47.12	-0.6
0.5	53.14	53.37	-0.4
-0.1	34.26	34.5	-0.7
-0.3	27.96	28.18	-0.8
-0.5	21.67	21.87	-0.9
Setpoint 950 mA			
0.1	45.52	45.06	1.0
0.3	52.566	52.125	0.8
0.5	59.61	59.1875	0.7
-0.1	38.478	38	1.2
-0.3	31.434	30.9375	1.6
-0.5	24.391	23.875	2.1
Setpoint 1050 mA			
0.1	49.836	49.375	0.9

Table 11. Analysis of the error propagation in the VCCL_dc_calculation function call versus different Isat value and current setpoints (continued)

Isat value	Floating point calculation of duty cycle	Fixed point calculation of duty cycle	Percent error between fixed and floating point calculation
0.3	57.633	57.1875	0.8
0.5	65.43	65.0625	0.6
-0.1	42.04	41.5625	1.1
-0.3	34.242	33.75	1.4
-0.5	26.445	25.9375	1.9
Setpoint 1150 mA			
0.1	53.22	53.68	-0.9
0.3	61.53	62.31	-1.3
0.5	70.089	70.87	-1.1
-0.1	44.67	45.125	-1.0
-0.3	36.12	36.56	-1.2
-0.5	27.57	27.93	-1.3
Setpoint 1450 mA			
0.1	66.05	66.68	-1.0
0.3	76.89	77.56	-0.9
0.5	87.72	88.5	-0.9
-0.1	55.22	55.81	-1.1
-0.3	44.38	44.93	-1.2
-0.5	33.55	34.06	-1.5
Setpoint 1550 mA			
0.1	70.36	71.18	-1.2
0.3	81.96	82.87	-1.1
0.5	93.56	94.56	-1.1
-0.1	58.76	59.56	-1.4
-0.3	47.16	47.81	-1.4
-0.5	35.56	36.12	-1.6
Setpoint 1650 mA			
0.1	74.67	75.62	-1.3
0.3	87.04	88.12	-1.2
0.5	99.41	100	-0.6
-0.1	62.31	63.18	-1.4
-0.3	49.94	50.68	-1.5

Table 11. Analysis of the error propagation in the VCCL_dc_calculation function call versus different Isat value and current setpoints (continued)

Isat value	Floating point calculation of duty cycle	Fixed point calculation of duty cycle	Percent error between fixed and floating point calculation
-0.5	37.57	38.25	-1.8
Setpoint 1750 mA			
0.1	79.01	80.06	-1.3
0.3	92.14	93.31	-1.3
0.5	100	100	0.0
-0.1	65.87	66.87	-1.5
-0.3	52.73	53.56	-1.6
-0.5	39.59	40.31	-1.8

8 Acronyms

Table 12. Acronyms

Acronym	Name
ABS	Antilock Brake System
ALU	Arithmetic Logic Unit
CNR	Current Not Reachable
ESC	Electronic Stability Control
ESP	Electronic Stability Program
MISO	Master Input Slave Output
MOSI	Master Output Slave Input
PWM	Pulse Width Modulation
SPI	Serial Peripheral Interface
TCS	Traction Control System
VCCL	Virtual Current Control Loop

9 Revision history

Table 13. Document revision history

Date	Revision	Changes
25-Jul-2008	1	Initial release.

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